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### 3 Definitions and Abbreviations

#### 3.1 DEFINITIONS

For the purpose of this standard, the definitions in Section 3.1 of the API Specifications 17J and 17K and the following apply:

- 3.1.1 Arrhenius plot:** Used to plot service life against the inverse of temperature for some polymer materials by means of a log-linear scale.
- 3.1.2 basket:** Used for storage and transport of flexible pipe (all pipes are laid freely into the basket).
- 3.1.3 birdcaging:** Buckling of the tensile armor wires, which results in significant radial deformation. It is usually caused by extreme axial compression.
- 3.1.4 buoyancy module:** A buoy used in significant numbers at discrete points over a section of riser to achieve wave shape riser configurations (see 4.4.6). See also definition for subsea buoy.
- 3.1.5 carousel:** Used for storage and transport of flexible pipe in very long lengths and rotates about a vertical axis. Pipe is wound under tension around the center hub.
- 3.1.6 chinese fingers:** A woven steel wire or fabric sleeve that can be installed over a flexible pipe and drawn tight to grip it for support or applying tension to the pipe.
- 3.1.7 chinese lantern:** Riser configuration used in shallow water offshore loading systems to connect a PLEM to a buoy directly above it. The upper and lower connections are vertical and excess riser length is supported by distributed buoyancy. See Figure 4.
- 3.1.8 flexible pipe system:** A fluid conveyance system for which the flexible pipe(s) is the primary component and includes ancillary components attached directly or indirectly to the pipe.
- 3.1.9 free-hanging catenary:** Riser configuration—see Figure 4.
- 3.1.10 heat trace:** An element incorporated into pipe structure to provide heating.
- 3.1.11 integrated service umbilical (ISU™):** A structure in which the inner core is a standard flexible pipe construction. Umbilical components are wound around the core pipe and covered with a protective outer sheath (see 4.3.4).
- Note: ISU is a trademark of Coflexip Stena Offshore.
- 3.1.12 J-S:** Riser configuration similar to a lazy-S (see Figure 4), with the exception that the lower catenary passes back underneath the subsea buoy. Also called reverse-S.
- 3.1.13 lazy wave:** Riser configuration—see Figure 4.

A

**3.1.14 lazy-S:** Riser configuration—see Figure 4.

**3.1.15 multibore:** Multiple flexible pipes and/or umbilicals are contained in a single construction. An outer sheath is extruded over the bundle (see 4.3.6).

**3.1.16 multiple configuration:** A riser system which has more than one riser connected at a mid-depth location, such as at a subsea buoy/arch system.

**3.1.17 ovalisation:** The out-of-roundness of the pipe, defined as the following:

$$\frac{D_{max} - D_{min}}{D_{max} + D_{min}}$$

where  $D_{max}$  and  $D_{min}$  are maximum and minimum pipe diameter respectively.

**3.1.18 rapid decompression:** Sudden depressurization of a system. Gas in the pipe will expand rapidly and may cause blistering or collapse of the internal pressure sheath or other gas-saturated layers.

**3.1.19 reel:** Large diameter structures used for storage of flexible pipe in long lengths and rotates about a horizontal axis.

**3.1.20 riser base:** Seabed structure (gravity or piled) for supporting subsea buoy/arch systems and/or riser/flowline connections (see 4.4.8).

**3.1.21 riser hang-off:** Structure for supporting riser at the connection to a platform (jacket, semi-sub, tanker, etc.).

**3.1.22 steep wave:** Riser configuration—see Figure 4.

**3.1.23 steep-S:** Riser configuration—see Figure 4.

**3.1.24 subsea buoy:** Concentrated buoyancy system, generally consisting of steel or syntactic foam tanks, as used in S-type riser configurations (see 4.4.5). See also buoyancy module.

**3.1.25 tensioner:** Mechanical device used to support or apply tension to a pipe during installation. Also called caterpillars.

**3.1.26 umbilical:** A bundle of helically or sinusoidally wound small diameter chemical, hydraulic, and electrical conductors for power and control systems.

## 3.2 SYMBOLS AND ABBREVIATIONS

The following symbols and abbreviations are used in this document:

17J/17K	API Specifications 17J and 17K
AISI	American Iron and Steel Institute
ANSI	American National Standards Institute

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
$C_D$	Hydrodynamic Drag Coefficient
$C_m$	Hydrodynamic Inertia Coefficient
DMA	Deplastizing Monitoring Assembly
DnV	Det norske Veritas
DOF	Degrees of Freedom
FAT	Factory Acceptance Test
FEM	Finite Element Method
FPS	Floating Production System
FPSO	Floating Production Storage and Offloading
GA	General Arrangement
GRP	Glassfiber Reinforced Plastic
HAZID	Hazard Identification Study
HAZOP	Hazard and Operability Study
HDPE	High Density Polyethylene
HIC	Hydrogen-induced Cracking
ID	Inside Diameter
ISO	International Standards Organization
MBR	Minimum Bend Radius
MWL	Mean Water Level
NACE	National Association of Corrosion Engineers
NDE	Non-Destructive Examination
NPD	Norwegian Petroleum Directorate
OCIMF	Oil Companies International Marine Forum
OD	Outer Diameter
PA	Polyamide
PE	Polyethylene
PP	Polypropylene
PLEM	Pipeline End Manifold
PU	Polyurethane
PVC	Polyvinyl Chloride
PVDF	Polyvinylidene Fluoride
QCDC	Quick Connect Disconnect
QDC	Quick Disconnect
RAO	Response Amplitude Operators
SSC	Sulfide Stress Cracking
TAN	Titrated Acid Number
TFL	Through Flowline
UV	Ultraviolet
VIV	Vortex Induced Vibration
XLPE	Cross-linked Polyethylene
$\sigma_u$	Material Ultimate Stress
$\sigma_y$	Material Yield Stress

A

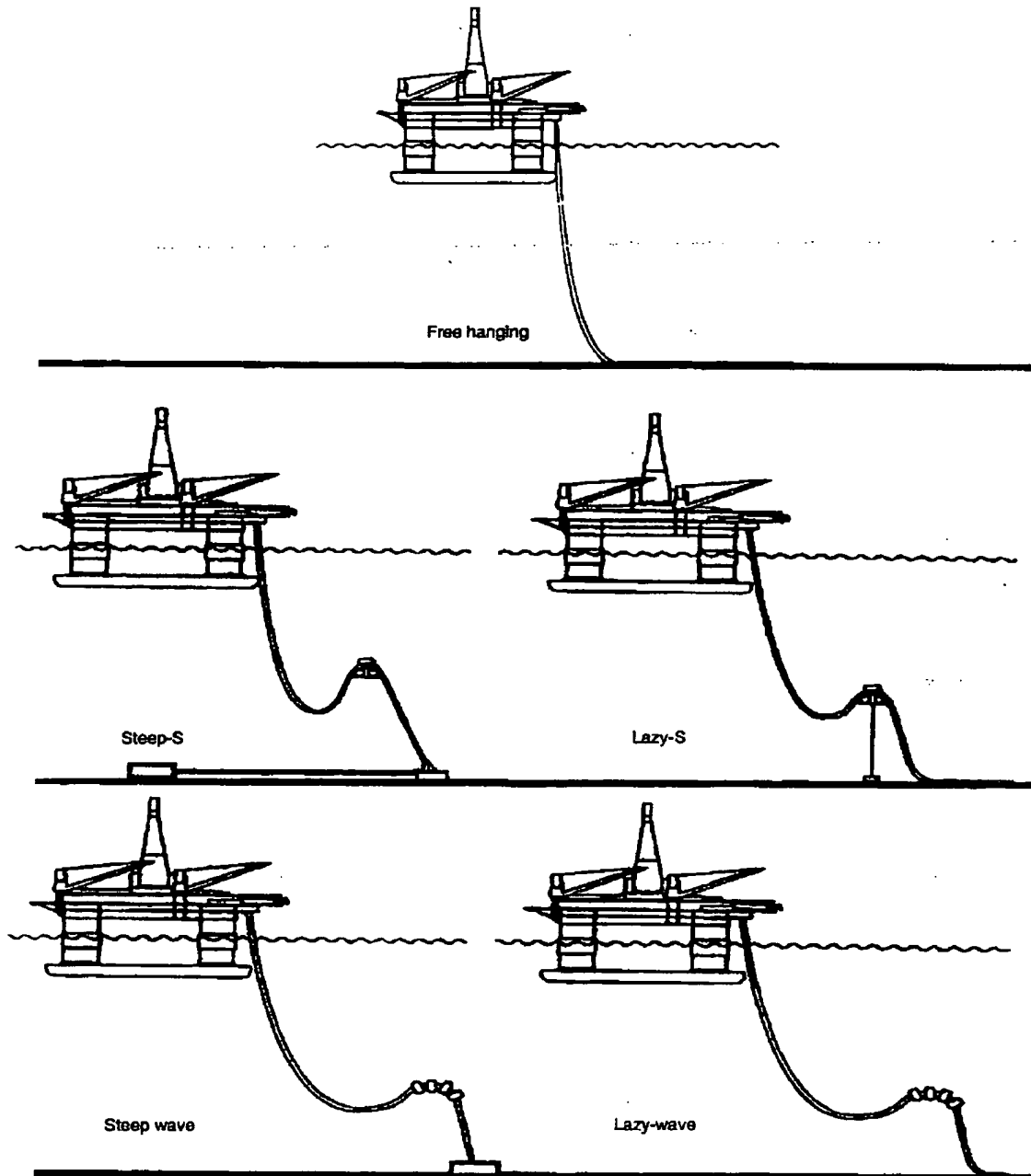


Figure 4—Examples of Flexible Riser Configurations

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f. Ball valves to be interlocked with release mechanism to ensure closure on disconnection (may not be required for all applications).

g. Simplified support structure (guide post funnels) to allow easy and safe reconnection.

h. Capability to periodically test release mechanism without releasing the riser or breaking primary seals (or if this is not feasible an alternative test procedure is required which includes retesting of primary seals after reconnection).

**4.4.4.4** Disconnect systems may have emergency shut-down valves on one or both sides of the interface. There also may be cases where no valve is required. Important considerations in this decision include: risk of disconnection, transported fluid, environmental concerns, and topsides valving.

#### 4.4.5 Subsea Buoys

**4.4.5.1** Subsea buoy/arch systems are used to achieve S-shaped riser configurations, including, lazy, steep, and reverse configurations (note that in the reverse configuration the lower catenary of the riser passes back underneath the buoy). The systems typically consist of one or more buoyancy tanks supported by a steel structure over which lies individual gutters (arches) for each riser. Two typical systems are shown in Figure 14. The buoyancy tanks may be constructed from either steel tanks or syntactic foam modules. The tanks may be positioned as shown in Figure 14.

**4.4.5.2** As an alternative, the S configuration may be achieved by using a fixed support instead of a floating buoy. An example of this is also shown in Figure 14. The main disadvantage of this system is the reduction in compliancy of the riser system.

**4.4.5.3** The subsea buoy/arch system is held in place by a riser base to which it is connected by tethers (lazy-S) or by flexible risers (steep-S). The subsea buoy/arch systems are designed to typically support two to six risers, though there is no theoretical limit on the number. The risers are held in place on the arch.

#### 4.4.6 Buoyancy Modules

**4.4.6.1** Buoyancy modules are used to achieve the wave shape riser configurations (lazy, steep, and pliant). A schematic of a typical module is shown in Figure 15. A number of modules (e.g., 30) are required to achieve the wave configuration and are generally sized (both length and diameter) to be about two to three times the pipe OD, though this depends on buoyancy and installation requirements. The number of modules is largely based on riser weight, water depth, offset

requirements, and manufacturing/commercial issues. As the modules are individually clamped to the riser, the design should ensure that they do not slide along the pipe or damage it. Some bonded flexible pipes have integral elastomer collars at intervals along the pipe to facilitate the attachment of ancillary devices. These collars are generally built and cured with the pipe.

**4.4.6.2** The buoyancy modules are typically composed of two components: an internal clamp and an syntactic foam buoyancy element. A polymer (e.g., polyurethane) casing provides impact and abrasion resistance. The internal clamp bolts directly onto the flexible pipe, and the buoyancy element fits around the clamp. The buoyancy element is generally in two halves that are securely fastened together. The density of the syntactic foam is selected based on the specified water depth and service life. A typical density is 350 kg/m<sup>3</sup>.

#### 4.4.7 Clamping Devices

**4.4.7.1** Clamping devices may be used in flexible pipe applications to connect ancillary components to the pipe, such as buoyancy modules, subsea arches, tethers, and bend restrictors. In addition, bundle clamps may be used to join several pipes together at discrete intervals, such as with piggy back lines (see example in Figure 16). The main component of bundle and piggy back clamps is a spacer device or body, which may be in two half sections. The body is provided with cylindrical recesses into which individual lines are fitted. The assembly is joined together with bolts or a set of circumferential straps. Alternatively, band straps may be used for static piggy back assemblies where they are needed only for installation.

**4.4.7.2** Care should be taken that excessive contact pressure is not caused. If high contact pressure is required, some type of protection shell should be fitted so as to distribute the applied load. The clamp design should also ensure that there are no sharp edges that may cause local overbending of the pipe.

#### 4.4.8 Riser and Tether Bases

**4.4.8.1** Riser bases are used to connect flexible risers to flowlines and may also be required to support subsea buoy/arch systems (e.g., steep-S configuration). Tether bases are used only to anchor subsea buoy/arch systems (e.g., lazy-S configuration).

**4.4.8.2** The riser base may be either a gravity structure, a piled structure, or a suction/anchor pad. Selection of gravity based or piled structure depends on applied loads and soil conditions. A typical riser base structure is shown in Figure 17. As an alternative, the flexible pipe may be connected directly to a


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**NEWSLETTERS**

## Flotation Technologies Raises the Bar for Distributed Buoyancy

Flotation Technologies

Flotation Technologies, Inc., a global leader in deepwater buoyancy systems, today unveiled its new, patent pending, Distributed Buoyancy Module. This product has been specifically designed to both decrease installation time and complexity, as well as improve overall performance over the previous marketplace offerings.

Distributed Buoyancy is used on flexible flowlines, umbilicals and steel catenary risers to hold subsea lines in a configured shape. These configurations allow the floating production facility free range of motion at the surface without putting undue stress on the subsurface lines.

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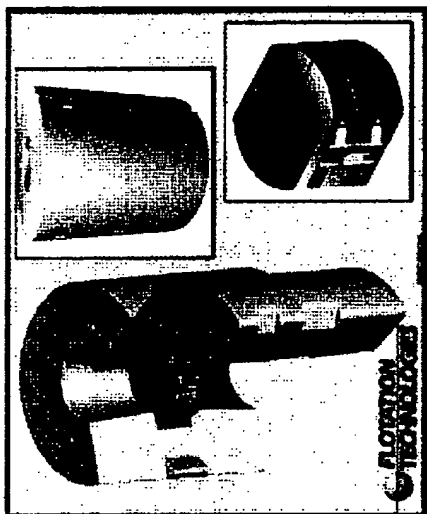
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"Since the mergers in the buoyancy market, two years ago, the marketplace has been lacking in competitive offerings of several products, Distributed Buoyancy has been the most obvious," commented Fred Maguire, Sales and Marketing Manager of Flotation Technologies. "This new product goes well beyond providing a second choice in the market; it provides a better choice."

Flotation Technologies' Distributed Buoyancy Module was designed with many enhancements over previous market offerings. The design criteria included easier installation, improved performance over a twenty-year life span, and an increase in on-vessel safety during installation. This new product offers several features which improve on current designs such as; a hinge and latch buoyancy element that offers easier handling and installation; a unique "W" shaped spring member on the internal clamp that allows for a larger variation in riser O.D. and improves long term performance; and a truly hinged internal clamp that eases installation and eliminates the need for pretensioning tools.

"This product release marks a significant step in Flotation Technologies' progressive and persistent product development plan and establishes us as a true engineered solutions provider," stated Tim Cook, President of Flotation Technologies. "As we carry on this path, we will continue to aggressively pursue new product development, improve our global manufacturing capability and continue to cultivate high-profile strategic relationships."

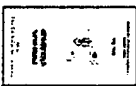
About Flotation Technologies

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Flotation Technologies, Inc. is a world leader in the design, manufacture, and marketing of deepwater buoyancy systems using high-strength Flotec(tm) syntactic foam and polyurethane elastomer products. Providing quick-turnaround, custom engineering and fabrication to the Offshore Oil, Oceanographic, Seismic and Government markets, Flotation Technologies delivers consistently reliable buoyancy and engineered products for a host of marine applications. Innovative syntactic foam products include flexible riser buoyancy, deepwater modular buoy, ADCP buoys, ROV/AUV buoyancy modules, pipeline/sled buoyancy, QuickLoc(tm) cable floats, Hardball(tm) umbilical floats, and elastomeric bend stiffeners, restrictors and cable protection. For more information on Flotation Technologies visit [www.flotec.com](http://www.flotec.com).

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##### **Pipelines and Risers**

This book delves into the design and engineering details of marine pipeline and riser systems with an eye toward both practical application as well as learning.



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## Distributed Buoyancy

Used to maintain a pre-defined configuration of subsea flexible risers and umbilicals (such as lazy, steep or plant waves) distributed buoyancy modules are a critical component of deepwater production. These configurations allow the vessel a full range of movement on the surface without putting undue stress upon the subsea lines, and decouple wave action from the seabed. Distributed buoyancy also helps prevent riser clashing and interference with mooring lines.



Flotation Technologies has made a major investment in capital equipment, engineering design and full scale testing to ensure that our patent pending buoyancy module and internal clamp meets or exceeds customer requirements while decreasing installation time.

## The Internal Clamp

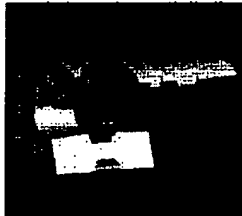
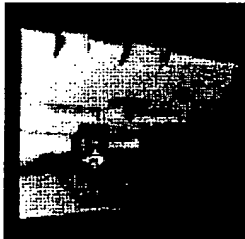
The internal clamp is the most important, and complex, component of the module. It securely attaches the exterior buoyancy to the subsea flexible while maintaining proper clamping force. This force must be maintained during the extreme loads generated during installation, as well as subsequent changes in pipe diameter for the life span of the field. Flotation Technologies' clamp is specifically designed to meet these stringent criteria. The internal clamp-body is made of high-density syntactic foam that is extremely resistant to creep and provides additional buoyancy to the module. All metallic elements are produced from super duplex stainless steel—providing superior corrosion resistance and tensile strength.





### Buoyancy Element

The exterior buoyancy element provides the uplift for the system. Flotation Technologies' patent pending design is provided as a unitary hinged module that latches around the internal clamp and is secured with a single locking pin. This two-third/one-third hinged design and unique snap-rod fastening system dramatically cuts installation time while increasing on rig safety. The buoyancy element is manufactured from a special grade of our Flotec™ syntactic foam cast into rotationally molded, high-strength polyethylene shells. Standard symmetrical modules can also be provided at customer request.



C

D



OTC 8523

## Low Cost Deepwater Hybrid Riser System

S.A. Hatton 2H Offshore Engineering Ltd.

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This paper was prepared for presentation at the 1997 Offshore Technology Conference held in Houston, Texas, 5-8 May 1997.

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### Abstract

The design and analysis of a cost effective multi flowpath production riser for deep and ultra deep water floating production systems is presented. The design is based on a bundled concept using beach fabrication and installation by near surface tow. The study has been funded by the DeepStar project and addresses water depths between 1300 and 2200m in the Gulf of Mexico. The riser is designed to interface with a semi submersible production vessel but may also be used with an FPSO with minor modifications.

The design approach minimises the riser steel weight and buoyancy requirements and achieves an optimum dynamic response through an efficient structural design and buoyancy distribution. This maximises riser flexibility and minimises hydrodynamic wave loading.

### Introduction

The definition of 'Deep water' changes every year. Operators are currently developing reservoirs in water depths up to 1500m and have drilling campaigns planned for depths beyond 2000m. Production technology for such water depths is likely to center on semi submersible and ship shaped floating production systems which are well established in shallower water depths.

The riser systems, used to transport production fluids between the seabed and vessel, will become an increasingly important aspect in deep water developments. Risers are dynamic systems which operate at high pressures and temperatures often with corrosive fluids. Consequently, risers are technically complex and the materials and methods of manufacture and installation make them costly. These issues are compounded as water depths increase due to higher loads and lengths involved making riser system selection and optimization even more complex.

Deep water developments to date have largely extended shallow water, flexible riser, technology through the development and application of new materials and manufacturing techniques. However, extending a successful shallow water solution to deep water is not necessarily the most economic or technically preferable approach. Whilst in shallow water high pipe flexibility is required to accommodate vessel motions, in deep water stiffer pipe may be considered due to the beneficial effect of water depth on riser system compliance.

In recent years new riser arrangements have been conceived to meet the challenge of deep water, offering significant commercial and technical advantages over conventional riser systems. These new riser systems utilize steel pipe which has a relatively low cost compared to flexible pipe. The importance of these new riser systems is significant. Commercially, they provide an alternative to the flexible riser but more importantly, in many cases, they provide a technical solution where no feasible solution exists with flexible pipe.

The two most promising riser concepts are the hybrid riser [1,4] and the steel catenary [2, 5]. Both concepts can be configured in a number of ways depending on application and even combined as in the case of the Tension Leg Catenary (TLC).

Whilst new riser configurations provide the industry with design solutions the selection of the most appropriate configuration for a particular application is complex, being dependent on many inter-related issues. The following sections discuss the design and development issues associated with a hybrid riser system and highlight the important design issues which should be considered during the riser selection process.

### Hybrid Riser Background

The hybrid riser is the first practical alternative to the full depth flexible riser to be implemented. In principle, it is a vertical bundle of steel pipes supported by external buoyancy. Compliance is provided by the use of short flexible pipe jumpers located near the surface to accommodate motions between the vessel and top of the riser.

The first hybrid riser was installed on Placid's Green Canyon development (469m). The riser was recently refurbished and extended in length for use on Ensearch's Garden Banks development (670m) [4, 7], see Figure 1. The main section of the hybrid riser consists of a central structural tubular, around which syntactic foam buoyancy modules are attached. Peripheral production and export lines run through the buoyancy modules and are free to move axially to accommodate thermal and pressure induced extension. The central structural member is connected to the riser base by a hydraulic connector and stress joint. Peripheral lines are connected to hard piping on the riser base interfacing with subsea flowlines via diverless pull-in porches. Near the surface flexible piping is connected between the upper goosenecks on the riser and porches on the pontoons of the semi submersible.

The hybrid riser implemented by Ensearch is installed in a similar manner to a drilling riser i.e. individual joints are assembled from the semi submersible to form a vertical string. This process is complex due to the size and weight of the riser joints and costly due to modifications required to the installation vessel and long installation durations. The latter limits the practicality of the concept for harsh environments and deeper water where weather windows are shorter.

### Optimized Hybrid

An alternative installation method proposed in [1] uses a near surface tow of a prefabricated riser bundle which is upended at the offshore site. Studies show this approach to be technically feasible and reduces the cost of installation due to the shorter installation duration and low cost installation spread. Furthermore, the approach allows the steel weight and buoyancy requirements to be reduced which enhances the riser response and reduces the capital cost. These beneficial features offer improved scope for using the hybrid concept in deep water and a wide range of environments.

The DeepStar hybrid riser is a development of this concept aimed at deep and ultra deep water (1300-2200m) in the Gulf of Mexico. The base case is for 1300m depth and sensitivities are conducted for 2200m. The riser is configured directly below a semi submersible production vessel (non offset). This allows the riser to be tethered to the vessel, reducing riser buoyancy requirements, base moments and length of the flexible jumpers. The latter is important not only from the cost aspect but also the effect of the weight and drag of the jumpers on the riser

response.

Unlike flowline bundles which are designed with a series of small diameter flowlines within a larger carrier pipe, the riser is designed with the smaller diameter lines arranged around the outside diameter of a central structural member. This arrangement offers the best compromise between design simplicity, structural stiffness, buoyancy, and method of fabrication.

The riser is configured to be near neutrally buoyant during installation. Syntactic foam buoyancy is used along the length of the riser to supplement that provided by the central structural member. A typical cross section of the riser, Figure 2, shows the arrangement of the central can, buoyancy and peripheral lines. The buoyancy diameter ranges from 2116mm at the base to 1844mm at the top. The change in buoyancy diameter accounts for variation of buoyancy density and steel weight with depth.

The central structural member for the Deepstar application is 30 inches in diameter. The riser has 13 peripheral lines, summarized in Table 1. The average riser weight in air is 2880kg/m (steel and buoyancy) and the total steel weight, for the 1300m riser is 2200Te.

Key design issues include:

- Configuration of structural member
- Material selection
- Buoyancy type and distribution along length
- Accommodation of peripheral line thermal expansion
- Method of peripheral line support
- Inspection philosophy
- Riser and peripheral line VIV suppression
- Thermal insulation
- Vessel interface requirements (semi or FPSO)
- Quick disconnect requirement (QDC)
- Ease of fabrication and assembly
- Installation procedures
- System risk and reliability
- Failure modes
- Capital and installation costs
- Redundancy and expandability

These issues are discussed in the following sections with reference to Figures 3 and 4:

### Structural Design

The diameter of the central structural member is relatively small compared to the buoyancy diameter. This produces a relatively flexible structure compared to configurations where the peripheral lines are located inside a larger diameter structural member. The small diameter member is also more resistant to hydrostatic collapse which is important near the base of the riser.

The wall thickness of the central member increases with depth to resist the increasing hydrostatic pressure. This also produces a riser which has a minimum bending stiffness near the top, unlike previous designs, which promote an even curvature along its length when loaded. This reduces the peak stresses and loads that typically occur at the riser base.

In ultra deep water hydrostatic collapse of the central member is increasingly difficult to prevent without specifying impractically large wall thicknesses. Three solutions to this problem are identified:

- Further reductions in the diameter
- Venting the central member and air filling with a cascade system at ambient pressure
- Using a composite structure

Reducing the diameter provides benefits but the reduced bending stiffness causes handling problems during launch. Venting the central member and cascade air filling prevents the problem of collapse but introduces the complexity of an air can system and prevents internal inspection. The use of a composite structure is preferred and is currently under evaluation. The arrangement consists of a steel and concrete sandwich. The concrete resists hydrostatic collapse whilst the steel sections accommodate the axial loads. As tension in the riser is relatively small, the wall thickness of the steel sections can be small. This arrangement is particularly suited to ultra deep water as the diameter of the central member can be maintained, or even increased, near the base of the riser. This maintains the correct stiffness distribution along the riser for optimum response and minimizes the volume of syntactic foam buoyancy required at maximum depth.

#### Buoyancy Type and Distribution

Buoyancy is provided by two components, the central member which is air filled and by syntactic foam which is evenly distributed along the riser length. This arrangement is different to existing designs which use large diameter air cans along the upper section and smaller volumes of syntactic foam along the lower sections where the cost of foam is highest. Some proposed designs eliminate the syntactic foam completely along the lower sections in an attempt to reduce the system cost. However, distributing the buoyancy evenly along the length has a number of important benefits:

- produces a smaller diameter in the wave zone and area of highest current thus reducing loading
- tension along the upper section can be maintained at a relatively low level which maximises compliancy and allows the riser to move sympathetically with the production vessel

- the buoyancy can be used to support and protect the peripheral pipes preventing vortex induced vibration (VIV)
- it reduces thermal losses
- simplifies riser installation by tow out

The distributed buoyancy configuration results in an even tension along the entire riser length. Analysis shows that this is efficient, requiring less total buoyancy than an arrangement using near surface air cans due to the higher hydrodynamic loading in the case of the latter.

The higher tension in the air can arrangement and intrinsically stiffer upper section results in higher base loads as deflections are concentrated near the base of the riser rather than evenly distributed along the riser length. This results in the need for a high specification taper joint, and foundations. Furthermore, the high upper riser tension and stiffness results in lower compliancy and results in a poor riser response, with respect to the vessel, complicating the jumper design and increasing their length.

A cost analysis of alternative buoyancy configurations combining syntactic foam and air cans demonstrates the cost effectiveness of the proposed approach. The use of distributed syntactic foam has further advantages over air cans as follows:

- Reduced design complexity
- Higher operational reliability
- Smaller maximum diameter which simplifies launch
- Neutrally buoyant during tow out
- No requirement for air up during installation

#### Riser Materials

API standard steel grades X65 and X75 are selected offering a balance between strength and weldability, the latter being important for simplifying fabrication and achieving NACE compliance.

#### Structural Member Internal Inspection

Internal inspection of the central structural member is possible during service by remote camera or intelligent pipeline pig. This is considered an important capability in view of the criticality of the central member to the structural integrity, long service life and inability for external inspection. To facilitate inspection a continuous internal bore, free from obstructions must be provided. Although the central member is fitted with isolation plugs to prevent flooding of the entire length in the event of rupture, these are designed to be removed on drill pipe or coiled tubing.

### Peripheral Line Support and Expansion

The peripheral lines are top suspended in tension rather than base supported in compression. This reduces loading on the buoyancy elements which must otherwise resist buckling of the lines. It should be noted that this approach does not have any effect on the total buoyancy requirement.

Expansion spools are required at the base of the riser, and at regular intervals along the riser, to accommodate expansion of the peripheral lines arising from thermal and pressure end cap effects. In ultra deep water, peripheral line expansion with respect to the central member can be up to 2000mm depending on production temperatures.

The proposed design uses compliant thermal expansion spools at equi-spaced elevations along the riser. The expansion spools use rigid steel pipe but provide sufficient compliancy due to their configuration which is similar to a 'Chinese lantern'. The use of multiple expansion spools along the riser length splits the total expansion between a number of spools and allows the weight of the peripheral lines to be transferred into the central member at regular intervals. Depending on current profiles, VIV suppression strakes may be a requirement on the exposed expansion spools.

### Connection and Sealing of Peripheral Lines

The all welded design places additional importance on the reliability of individual components, none more so than the peripheral line base connections due to their relative inaccessibility in service. Each peripheral line terminates at the base in an upward facing hub. Individual ROV installed rigid spools with hydraulic connectors each end are used to connect between the peripheral lines on the riser and template pipework. If required, the spools can be retrieved during service for inspection or replacement.

### Vortex Induced Vibration

The possibility of vortex induced vibration of the riser bundle is an important issue in high current environments such as the Gulf of Mexico. Analysis shows the requirement for VIV suppression strakes over the upper half of the riser. Whilst this increases the drag coefficient and thus loading, it is a proven way to control VIV response and resulting fatigue damage. Other methods of reducing VIV include profiling of the buoyancy modules and alternating buoyancy diameters. The latter may benefit from results of current studies on deep water drilling risers. The use of staggered or profiled buoyancy modules has the benefit of reduced drag and lower probability of damage during launch.

### Riser Top Assembly

Each peripheral line is terminated at the top of the riser bundle by goosenecks. These allow flexible jumpers to be connected in

a catenary configuration to the vessel. The goosenecks are located at a depth of 35m below the mean sea level. This elevation is selected as a compromise between increasing the length of the jumpers (and their cost), and minimizing the hydrodynamic drag loading. The tether from the production vessel is connected directly to the central 30 inch member where it exits from the top of the riser. A hydraulic connector and internal isolation plug is used to provide double isolation of the central member and access for internal inspection tooling.

### Emergency Quick Disconnect (QDC)

The design philosophy assumes the riser is not disconnected from the vessel during service however, disconnection is feasible if required. During normal service the riser is tethered to the vessel using a motion compensated tensioner that maintains a tether tension of approximately 100Te. This controls the response of the top assembly and supplements the tension provided by the buoyancy modules. However, the riser is able to free stand providing the peripheral lines are air filled. This provides an additional base tension of 300Te allowing the riser to accommodate significant current loading. Should it be necessary for the riser to remain disconnected during loop current conditions, additional temporary buoyancy in the form of air bags or foam may be required.

### Riser Base and Connector

The riser is connected at the seabed to a lightweight fabricated steel base piled to the seabed. The template is hexagonal in shape with flowline porches located around the periphery. Six 30 inch x 30m piles are used to react the riser loads but this is dependent on the local seabed conditions. A central high capacity hydraulic collet connector is machined integrally with the lower taper joint and provides a proven method for transferring riser loads into the riser base and foundation.

### Analysis

The riser is analyzed for a range of environmental load cases using both regular and random wave techniques. Analysis is conducted using FLEXCOM3D, a time domain, marine structures analysis package, and SHEAR7 for VIV assessment. Care must be taken to ensure the riser bundle is correctly equivalenced and de-equivalenced during the analysis process such that loads in the individual lines are correctly assessed. The flexible jumpers must also be incorporated in the model as their weight and drag has a significant influence on the response of the riser top assembly. Table 2 summarizes the key extreme storm results showing an acceptable response for all load cases. Table 3 presents a summary of the fatigue contributions along the riser length. It is concluded that a 250 year fatigue life can be achieved providing VIV suppression strakes are used on the top section of the riser and double side welding techniques are adopted for fabrication of the central structural member.

Tow analysis is conducted for both regular and random seas and upending analysis is conducted to develop offshore procedures. The resonant period of the riser during tow is well above the dominant installation wave period as a result of its long length, and weight. Analysis demonstrates the riser can be safely towed at up to 4 knots in seastates up to an  $H_s$  2.8m.

#### Fabrication and Installation

The key to the proposed riser design is the method of fabrication and installation. The riser is beach fabricated and launched in 3 sections using flowline bundle techniques. Flooding of the central member during launch is prevented by inflatable plugs located in the ends of each section. After launch, each section is flanged together at a protected shallow water site. The thermal expansion spools are fitted and the entire assembly pressure tested prior to tow out.

The riser is installed using a near surface tow and upended at the offshore site using low cost installation vessels. The tow duration is estimated to be 2-3 days and full installation can be achieved within a short duration, 7-10 days. The riser tow and upending procedure is developed to minimize offshore operations and ensure high reliability.

An alternative fabrication and launch method uses a low cost pipelay barge moored in a protected shallow water location. The central structural member may be fabricated and launched into the water over the stinger, complete with attached buoyancy modules. The peripheral lines can then be fabricated on the pipe barge and assembled into the floating bundle.

#### Offset Hybrid

The proposed hybrid riser configuration is not suited for use with an FPSO even in a mild environment due to the inability to achieve an acceptable jumper response within the constraints of conventional turret dimensions. To overcome this problem the riser is offset from the vessel to increase the jumper length and improve the response.

Offset distances of 200-300m are necessary depending on water depth and vessel mooring stiffness. In the offset configuration the riser must self stand, as it is impractical to apply tension from the vessel. This requires additional buoyancy to be applied to the riser to resist current loading and prevent excessive riser deflections. The load applied by the jumpers to the top of the riser has a significant effect on both the mean offset and dynamic response of the riser as the total jumper weight on the tower is in the order of 500-600Te.

To provide additional buoyancy an upper air can is proposed which is installed from the semi after the main riser section has been towed out and upended. The air can is connected to the riser via an articulated flex joint which prevents the generation of high bending loads due to the action of current and wave

loading on the air can section. The peripheral lines are terminated below the air can. Analysis of this arrangement shows it is well suited for application with an FPSO (spread and turret moored) even in a harsh environment and depths of 2200m.

#### Line Numbers and Weights

Studies have considered between 18 and 25 peripheral lines with diameters ranging from 6 to 12 inches. 25 lines is considered to be near the maximum number that can be practically accommodated in a single hybrid assuming that the majority of lines are of 10 and 12 inches diameter.

Hybrid risers with larger numbers of lines have a high weight (approx 8.0 Te/m) and require buoyancy diameters in excess of 3000mm. This is considered to be near the limit of what can be economically fabricated, assembled and launched.

Risers with high numbers of peripheral lines present problems at the base and vessel interface. Difficulties arise in configuring the flowline interface and surface jumpers. A smaller number of larger lines is preferred to a large number of smaller lines. Where a large number of lines is required the preferred solution is to split them between two separate risers located either side of the vessel. This approach can be attractive as it offers a number of benefits:

- allows jumpers to be routed to both sides of the vessel (turret or pontoon)
- simplifies the design of the riser top assembly and goosenecks
- simplifies fabrication and launch
- reduces the size of key components and eases manufacturability
- reduces the project risk due to redundancy
- allows a phased development to be considered

Splitting the riser into two has a cost impact but this may be acceptably small in view of other advantages offered. The key cost difference is the installation of two templates and two risers. This may be achieved at the same time to reduce costs or staggered to suite the project schedule.

#### Failure Modes

Low tension in the riser and elimination of air can buoyancy results in a safer system in the event of structural failure of the riser. The tension in the central member at any point along the length is low enough to be accommodated by the peripheral lines in the event of failure, preventing the riser from rising to the surface and endangering the safety of the production vessel. Furthermore, the elimination of vented air can buoyancy excludes the possibility of a large release of air which may affect vessel stability and riser integrity.

### Production Scenarios and Applications

The hybrid riser is particularly suited to applications where wells can be drilled from a central location. The riser can then be installed directly adjacent to the subsea wells in a manner that allows simultaneous production, drilling or workover from the production vessel. This eliminates the high cost of a drilling and work over vessel but the cost of drilling facilities and impact on deck payload must be considered.

The other main benefit of the hybrid over steel catenary or flexible riser systems is it allows tight control of the flowline routing and seabed layout. Steel catenary and flexible risers have a large plan area and this, when combined with the vessel mooring pattern, neutralises significant portions of the seabed. If large numbers of risers are required, it may be necessary to distribute the risers radially around the vessel, particularly if a turret moored FPSO is considered, to prevent riser clashing and ensure a balanced load on the vessel and mooring system. As a result, it may not be possible to orientate the risers in the preferred direction ie. towards wellhead and therefore costly flowline detours may be necessary to route the riser to its final destination.

### Costs

The estimated installed cost of the 1300m DeepStar riser for use with the semi submersible is £26 million, Figure 5. The total hardware cost is £19 million, Figure 6. Buoyancy and flexible jumpers are the highest single cost items.

A cost analysis [5] conducted with flexible riser systems indicates installed cost savings in the order of 40-50%. When compared with a steel catenary riser system then the total cost is similar but highly dependent on the adopted catenary configuration and assumed installation costs.

The installed cost of an equivalent offset hybrid is £29 million which accounts for the higher cost of the jumper hoses and air can top assembly. The installed cost of a non offset configuration for 2200m is £37 million ie. a cost increase of only 40%.

### Conclusions

The hybrid riser is a competing technology for deep and ultra deep water applications and may be evaluated for use with a range of production vessels and environments. The use of an all welded design with installation by tow out and upending offers scope to reduce material and installation costs in deep water and improve dynamic response compared to existing configurations.

### Acknowledgments

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Function	OD (Inch)	No. off	Design Pressure (psi)
Production	8-5/8	6	5000
Gas Injection	8-5/8	2	5000
Water Injection	8-5/8	4	5000
Hydraulic Control	3/4	6	5000
Chemical Supplies	3/4	6	5000
Methanol	2-3/8	1	5000

Table 1 Riser Nos and Sizes

Parameter	Vessel Offset (5%) Water Depth (Intact Mooring)	Vessel Offset (10%) Water Depth (Intact Mooring)	Vessel Offset 15% Water Depth (Failed Mooring)	Load Case
Max Base Tension (kN)	1399	1500	1725	API High Wave
Min Base Tension (kN)	1096	1270	1425	API High Wave
Max Base Moment (kNm)	2808	4143	5754	Loop Current Storm
Min Base Moment (kNm)	1070	2453	4111	API High Wave
Max Top Section Vm/Yield Stress	0.454	0.415	0.355	Loop Current
Max Mid Depth Vm/Yield Stress	0.328	0.328	0.325	API High Wave
Max Taper joint Vm/ Yield Stress	0.457	0.613	0.788	Loop Current Storm
Min Jumper Bend Rad. (m)	-	-	4.0	API High Wave

Table 2 - Summary Extreme Storm Analysis Results

Fatigue	Top	Mid Depth	Taper Joint
First Order Damage 1/Yr	0.138E-2	0.441E-4	0.801E-3
Second Order Damage 1/Yr	Negligible		
VTV Damage 1/Yr	0.15E-4	0.109E-4	0.162E-5
Total Damage 1/Yr	0.136E-2	0.55E-4	0.80E-3
Damage in 250 years	0.341	0.0137	0.20
Tow Out Damage	0.205E-2	0.377E-3	0.334E-3
Total Damage in 250 years	0.343	0.014	0.200
Factor of safety on 25 years	30	700	50

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**Table 3 Fatigue Damage Summary**

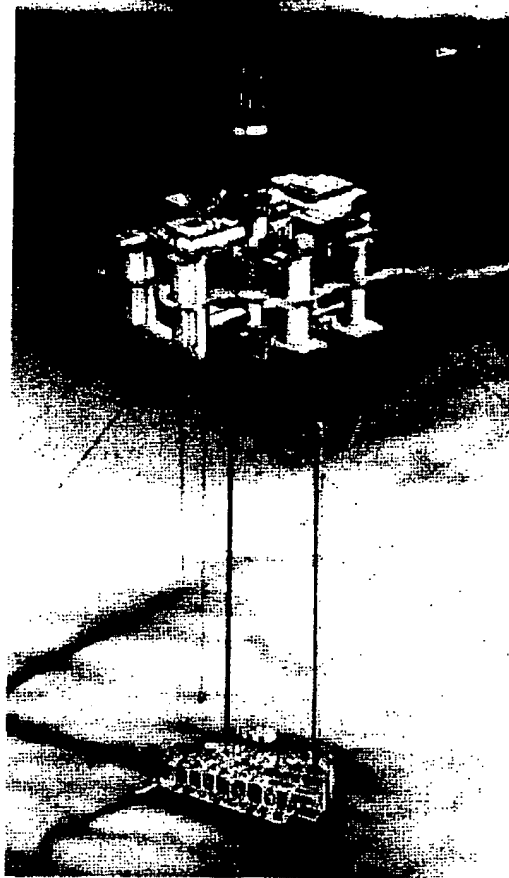


Figure 1 Placid Riser Arrangement

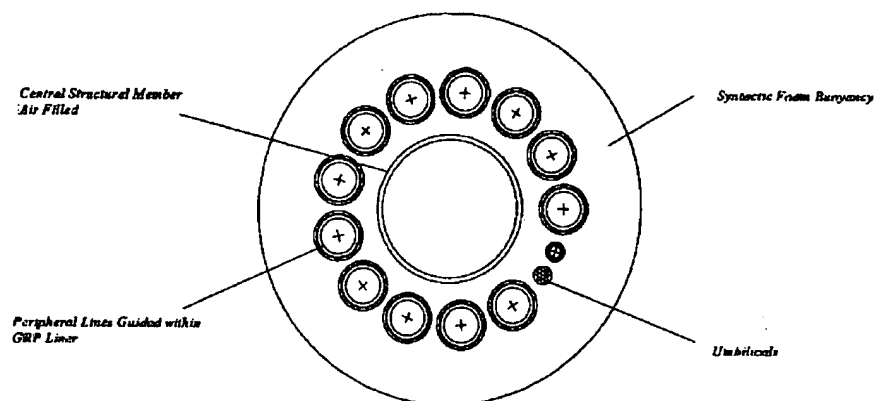


Figure 2 Riser Section Arrangement

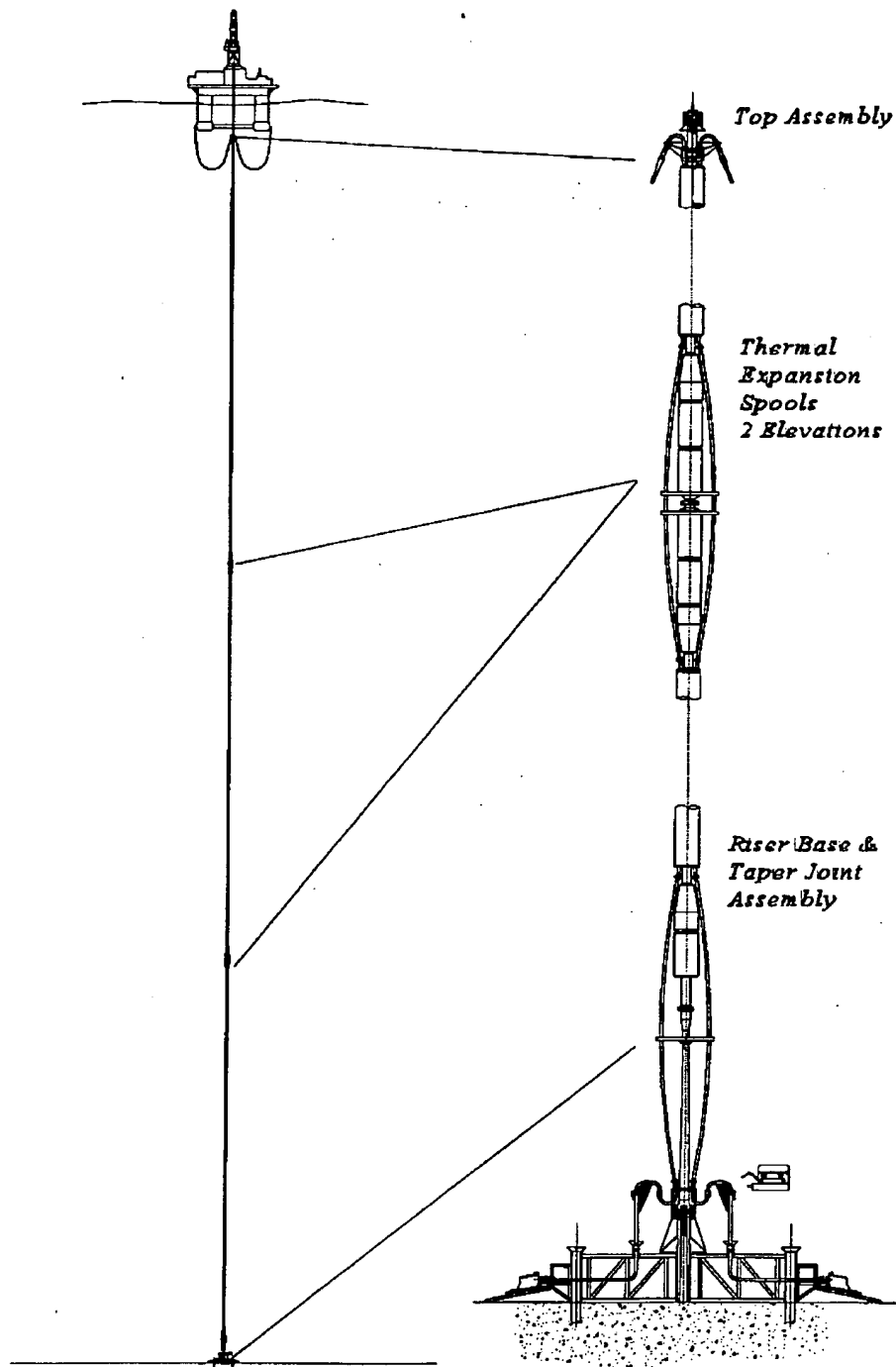


Figure 3 Non Offset Hybrid Riser General Arrangement (1300m Water Depth)

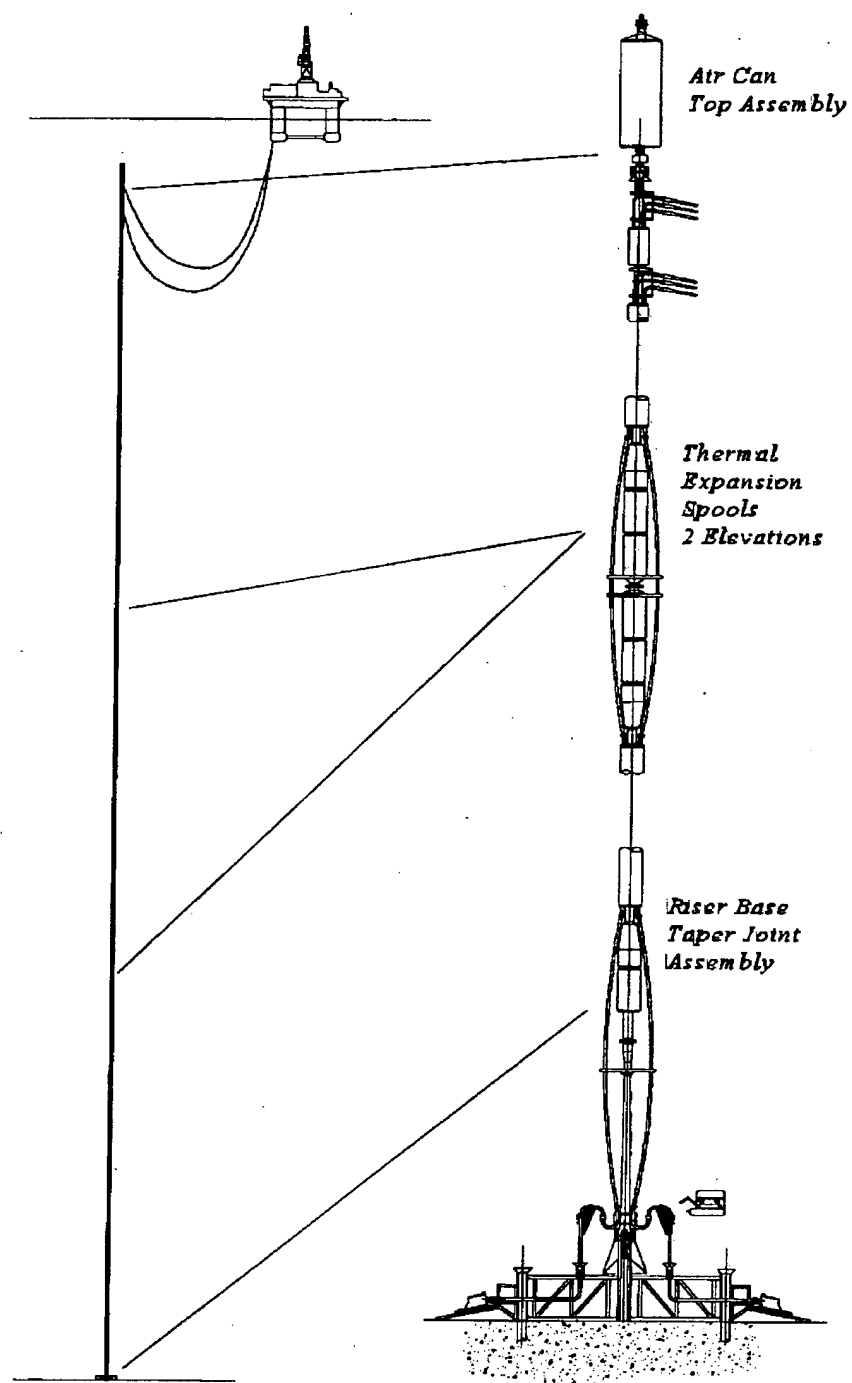


Figure 4 Offset Hybrid Riser General Arrangement (1300m Water Depth)

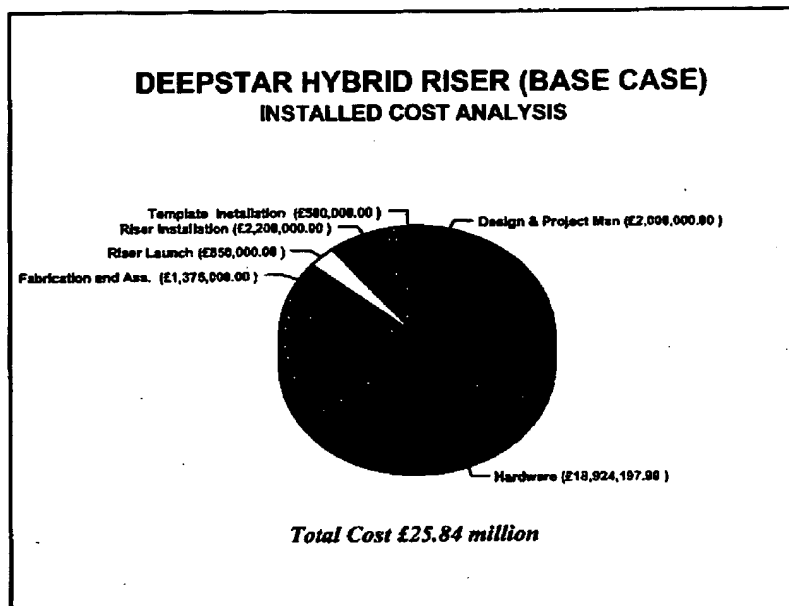


Figure 5 Installed Cost Summary (1300m Water Depth)

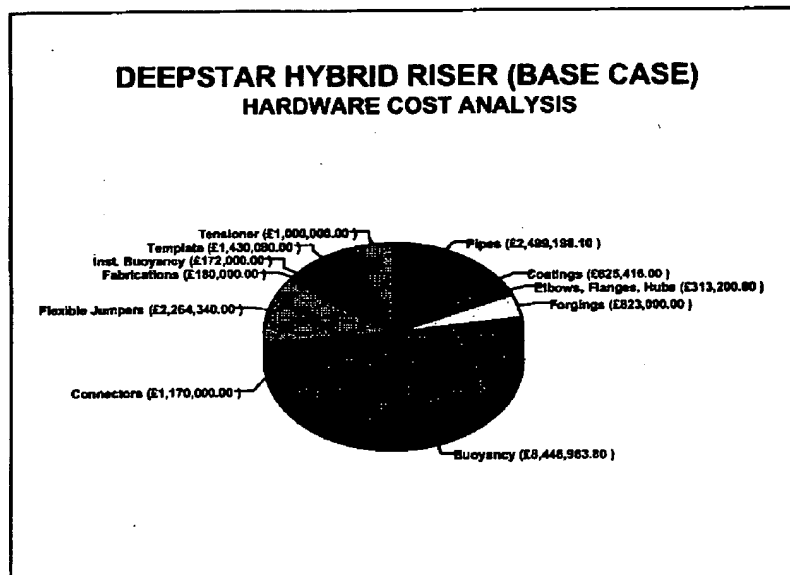


Figure 6 Hardware Cost Breakdown (1300m Water Depth)

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